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A cable, a method of constructing a cable, and use of a cable

The present invention relates to a cable with at least one cable core having a number of conducting layers which are mutually separated by isolating layers, where said conducting layers include electrical conductors which are arranged helically with predetermined pitch angles, and in particular to an electrical cable with reduced AC loss.

When using an electrical cable it is generally desirable to obtain as low power loss as possible. Cables adapted to have low losses are known from the prior art. The prior art discloses AC cables with at least one cable core having a number of conducting layers which are mutually separated by isolating layers. The conducting layers are normally formed by electrical conductors which are arranged helically with predetermined pitch angles.

The innermost conductor which may be of superconducting material is normally wound spirally around a central former and hereby forms a conducting layer. Likewise, the other conducting layers which may also be of superconducting material are normally wound spirally around the isolating layers adapted to separate the conducting layer. The number of conducting layers required depends on the desired use of the cable and on the current carrying capability of the tapes used.

The current distribution between the layers depends on the winding pitches of the conductors as the inductance between the layers depends on the winding pitches. According to the prior art pitches are therefore varied from layer to layer in a given way. As a result the

current will distribute more equally between the conducting layers resulting in reduced AC losses.

WO 96/39705 discloses a cable with a central carrier body around which electrical conductors are arranged helically with predetermined pitch angles in at least three conductor positions. The pitch angles of the conductors in the individual conductor positions are selected such that they either increase or decrease in steps from position to position between a first value of the radial innermost conductor position and a second value of the radial outermost conductor position.

Even though the AC cables according to the prior art are found to be useful, they have the drawback that quite large variations of the winding pitches are required in order to obtain an equal current distribution. Furthermore, in practice, it is difficult to produce cables with these large variations in pitches.

The object of the invention is to provide an AC cable with low AC-loss and which overcome the disadvantages of the state of the art cables.

This object is achieved by an AC cable with at least one cable core having a number of conducting layers which are mutually separated by isolating layers, where said conducting layers include electrical conductors which are arranged helically with predetermined pitch angles, in which at least one of said isolating layers has a thickness different from the thickness of at least one of the other isolating layers, and/or at least one of said isolating layers includes material which is different from the material of at least one of the other isolating layers.

Hereby, a homogenous distribution of the current in the cable and thus a reduction of the AC losses in the cable is obtained. Further, a cable having less variations of the winding pitches compared to cables of the prior art can be obtained. This is of interest as strongly varying pitches lead to differential thermal contraction of the different layers during cool-down of the cable.

The invention also relates to a method of producing a cable of the above mentioned type.

In accordance with one embodiment of a cable according to the invention at least one of said isolating layers is thicker than the neighbouring isolating layers.

In accordance with another embodiment said thickness of said isolating layers decrease in steps from layer to layer between a first value of the radial innermost isolating layer and a second value of the radial outermost isolating layer.

In a particularly expedient embodiment, said pitch angles of said conductors in said individual conductor layers are equal or approximately equal. This is of interest as small variation of the pitches from layer to layer are beneficial for the mechanical properties of the cable.

In a preferred embodiment said pitch angles of said conductors in at least one of said individual conductor layers is different from the pitch angles of the conductors in at least one of the other of said individual conductor layers. Hereby, the variation of the thickness and the material of the isolating layers can be combined in order to obtain an optimal reduction of the AC-losses in the cable.

Preferably, said pitch angles of said conductors in said individual conductor layers are selected such that they either increase or decrease in steps from layer to layer between a first value of the radial innermost conductor layer and a second value of the radial outermost conductor layer.

Preferably, said conducting layers includes conductors with windings in a reverse direction in respect to the conductors of at least one of the neighbouring conducting layers. Hereby, an additional effect of a increased torsional strength of the cable is obtained.

In a preferred embodiment, said isolating layers include polyamide, polyester, paper, polyester imprinted paper or semiconductor material.

Preferably, said conductors includes super-conducting material. In a particularly expedient embodiment, said super-conducting material is high-T_c super-conducting material.

The present invention also relates to the use of a cable according to the invention as a power cable.

The present invention will now be described more fully with reference to the drawings, in which

Figure 1 shows a schematic cross section view of the current carrying part of a cable according to the prior art,

Figure 2 illustrates a first embodiment of the current carrying part of a cable according to the invention,

Figure 3 illustrates a second embodiment of the current carrying part of a cable according to the invention, and

~~Figure 4 illustrates a third embodiment of the current~~ carrying part of a cable according to the invention.

Generally, it is desirable to obtain as low power loss as possible in electrical cabels, e.g. when the cable is used as an AC power cable.

The prior art discloses cables with at least one cable core having a number of conducting layers which are mutually separated by isolating layers. The conducting layers are normally formed by electrical conductors which are arranged helically with predetermined pitch angles.

Figure 1 is a cross section view of a cable 1 according to the prior art and illustrates the structure of the cable 1. The cable 1 includes a central former 2 around which an electrical conductor is arranged hellically with a predetermined pitch angle. The conductor hereby forms a conducting layer 3 which is adapted to carry an electrical current in the cable 1.

As can be seen from the figure, the shown cable 1 includes four conducting layers 3, 6, 9 and 12. The conducting layers are mutually separated by so-called isolating layers 5, 8 and 11, i.e. conducting layers 3 and 6 are separated by the isolating layer 5, conducting layer 6 and 9 are separated by the isolating layer 8, and so forth. The isolating layers have a given constant or an approximately constant thickness.

The other conducting layers 6, 9 and 12 also include conductors which are wound spirally around the isolating layers adapted to separate the conducting layer. The

number of conducting layer in the cable depends on the desired use of the cable and on the current carrying capability of the tapes used. As this type of cables are well known from the prior art the varying pitch angles are not illustrated here.

The current distribution between the layers depends on the variation of the winding pitches of the conductors as the inductance between the layers depends on the winding pitches. According to the prior art the pitches are therefore varied from layer to layer in a given way. In the shown embodiment the pitch angles of the conductors in the conducting layers 3, 6, and 9 and 12 all have a given different value. As a result the current will distribute more equally between the individual conducting layers resulting in reduced AC losses compared to the losses in a similar known cable having an equal or approximately equal pitch in all layers.

According to the invention the layer radii and/or the materials of the isolating layers is selected in to fulfil (at least approximately) the following inductance equation:

$$V_i = M_{ij}\ I_i \qquad \text{for:}\quad I_i = I_j \text{ and } V_i = V_j$$

Where M_{ij} is an inductance matrix, and V_i and I_i are the layer voltage and current. By definition all the V_i are identical (the layers are in parallel). As indicated it is desirable to achieve a cable in which the I_i are also identical. In practice, this is achieved by varying the layer radii and/or the materials of the isolating layers. Two examples are given below.

It is noted that the high AC loss of the cables having approximately equal pitch in all layers is due to the

fact that the current concentrates in the outer layers of the cable. This leads to losses that are virtually identical to the ones found in a solid tube conductor of the dimensions of the cable.

The drawback of cables according to the prior art is the quite large variations of winding pitches which are required to obtain a desired equalization of the current distribution. Cables having these large pitch variations are often technically unrealisable. In addition, strongly varying pitches may not be desirable as they lead to differential thermal contraction of the different layers during cool-down of the cable. Further, small variation of the pitches between the layers as well as small pitches are desirable as these result in beneficial mechanical properties of the cable.

Figure 2 illustrates a first embodiment of a cable according to the invention. The figure is a cross section view of a cable 15 having a central former 2 and three conducting layers 3, 6 and 9. The conducting layers are mutually separated by isolating layers 16 and 18 as shown in the figure. For example, the isolating layers include mylar, polyamide, polyester, paper, polyester imprinted paper or semiconductor material, and may also include magnetic material.

In the shown embodiment of a cable according to the invention, the isolating layers 16 and 18 varies in thickness, that is, the thickness of the isolating layers decrease in steps from layer to layer between a first value of the radial innermost isolating layer and a second value of the radial outermost isolating layer. By varying the thickness of the isolating layers of the conductor the inductance between the conducting layers are varied. By performing a suitable selection of the

thickness of the individual isolating layers of the cable the current will distribute more equally between the conducting layers resulting in reduced AC losses. Below, two examples of cables according to the invention are given.

In a first example the cable consists of 8 conducting layers. The central former has an outer diameter of 35 mm, and the thickness for the superconducting tape with insulation is 0.23 mm. In the shown example, Bi2223 is used as superconducting material and mylar is used as the isolating material. The winding pitches are as follows. It is noted that negative pitches denote opposite winding directions of the conductor.

Layer	1	2	3	4	5	6	7	8
Radius/mm	19,23	19,00	18,77	18,54	18,19	17,96	17,73	17,50
Pitch/mm	150	215	340	740	-900	-335	-220	-180

The thickness of the four innermost layers is constant and of the four outermost layers is constant. However, there has to be a gap of 0.12 mm between layers 4 and 5 in order to achieve equal currents in each layer and thus lowest losses at the critical current.

A second example shows a cable with four non-equidistant layers with almost equal winding pitches. The radius given is the radius on which a superconducting tape of 0.18 mm thickness has to be wound.

Layer	1	2	3	4
Radius/mm	18.9	18.65	18.2	17.5
Pitch/mm	250	270	290	290

It is noted that the resulting cable has an almost homogeneous current distribution in the three outermost layers.

It is further noted that the pitches are rather small and almost equal which improves the mechanical (bending) properties of the cable. Differential contraction of different layers is minimised.

A further improvement of the mechanical properties (torsional strength) of the cable can be achieved when the conductors of at least one of said conducting layers have reverse winding direction in respect to the conductors of at least one of the neighbouring conducting layers.

As was seen above the variation of thickness of the isolating layers can be combined by a variation of pitch angle of the conducting layers.

It is noted that the conductors may include high-T_c superconducting materials, e.g. Y-Ba-Cu-O or (Bi,Pb)-Sr-Ca-Cu-O. The conductors may also include low-T_c superconducting materials, e.g. Nb-based superconducting materials. Or, the conductors may even be conventional conductors. It is further noted that the conductor may be formed as tapes, e.g. multi-filament superconducting tapes.

Figure 3 illustrates a second embodiment of a cable according to the invention. The figure shows a cross section view of a cable 20 which include a central former 2 and four conducting layers 3, 6, 9 and 12. The conducting layers are mutually separated by a first isolating layer 21, a second isolating layer 22, and a third isolating layer 23; see Figure 3.

In the shown embodiment the isolating layers all have the same thickness, but in contrast to the prior art cable shown in figure 1, the material of the isolating layers can vary from layer to layer, i.e. the first, second and third isolation layers 21, 22, 24 consist of a first, second and third isolating material, respectively. Magnetic materials may be included in some, but not all layers.

Figure 4 illustrates a third embodiment of a cable according to the invention. The figure shows a cross section view of a cable 25 which include a central former 2 and four conducting layers 3, 6, 9 and 12. The conducting layers are mutually separated by a first, second and third isolating layer 26, 27, 28; see Figure 4.

In this embodiment both the thickness of the isolating layers and the material of the isolating layers varies from layer to layer. As can be seen from the figure, the thickness of the isolating layers 26, 27 and 28 decrease in steps from layer to layer between a first value of the radial innermost isolating layer 26 and a second value of the radial outermost isolating layer 28. As mentioned, the material of the isolating layers can also vary from layer to layer, and may include magnetic materials.

It should be noted that the central former of a cable according to the invention can be formed of any isolating material, conventional conducting material, or superconducting material depending on the intended use of the cable. The described principle of a cable having varying thickness of the individual isolating layers can also be used on cables without a central former.

Further, it should be noted that a cable according to invention can include an arbitrary number of conducting layers. Likewise, the thickness of the isolating layers and the pitches can be varied arbitrarily.

In another embodiment of the invention one or more of the isolating layers consists of a number of layers. Hereby, such isolating layers - which may be called multi-layered isolating layers - can be composed of different materials giving the isolating layer a desired mechanical and/or electrical characteristics.

It is further noted, that the desired reduction of the AC losses can be reached as a combination of the effect obtained by the variation of the thickness of the isolating layers and/or the isolating material. In addition, pitches of the conducting layers may also be varied.

Although preferred embodiments of the present invention have been described and shown, the invention is not restricted to those. It may also be embodied in other ways within the subject-matter defined in the following claims. For example, the same principle can be used in multi-core cables, i.e. a cable of the described type can be a single core of a multi-core cable having one or more of similar cores and/or one or more of state of the art cable cores. A cable core may also include a number of sub-cores which may or may not have structure of a core according to the invention. As an other example, the cable can include one or more non-concentric conducting and/or isolating layers. Further, one or more of the conducting and/or isolating layers can be formed to have an arbitrary shape, e.g. oval or approximately oval, elliptical or approximately elliptical.

P a t e n t   C l a i m s :

1. A cable with at least one cable core having a number of conducting layers which are mutually separated by isolating layers, where said conducting layers include electrical conductors which are arranged helically with predetermined pitch angles c h a r a c t e r i z e d in that at least one of said isolating layers has a thickness different from the thickness of at least one of the other isolating layers, and/or at least one of said isolating layers includes material which is different from the material of at least one of the other isolating layers.

2. A cable according to claim 1, c h a r a c t e r i z e d in that at least one of said isolating layers is thicker than the radial outermost of the neighbouring isolating layers.

3. A cable according to claim 1, c h a r a c t e r i z e d in that said thickness of said isolating layers decrease in steps from layer to layer between a first value of the radial innermost isolating layer and a second value of the radial outermost isolating layer.

4. A cable according to one or more of claims 1-3, c h a r a c t e r i z e d in that said pitch angles of said conductors in said individual conductor layers are equal or approximately equal.

5. A cable according to one or more of claims 1-4, c h a r a c t e r i z e d in that said pitch angles of said conductors in at least one of said individual conductor layers is different from the pitch angles of

the conductors in at least one of the other of said individual conductor layers.

6. A cable according to claims 5, c h a r a c t e r i z e d in that said pitch angles of said conductors in said individual conductor layers are selected such that they either increase or decrease in steps from layer to layer between a first value of the radial innermost conductor layer and a second value of the radial outermost conductor layer.

7. A cable according to claims 5, c h a r a c t e r i z e d in that at least one of said conducting layers includes conductors with windings in a reverse direction in respect to the conductors of at least one of the neighbouring conducting layers.

8. A cable according to any one of the preceding claims, c h a r a c t e r i z e d in that said isolating layers include mylar, polyamide, polyester, paper, polyester imprinted paper, semiconductor or magnetic material.

9. A cable according to any one of the preceding claims, c h a r a c t e r i z e d in that said conductors includes super-conducting material.

10. A cable according to claim 9, c h a r a c t e r i z e d in that said super-conducting material is high-T_c super-conducting material.

11. A method of constructing a cable with at least one cable core having a number of conducting layers which are mutually separated by isolating layers, where said conducting layers include electrical conductors which are arranged helically with predetermined pitch angles c h a r a c t e r i z e d in that the thickness of at

least one of said isolating layers is selected to be different from the thickness of at least one of the other isolating layers, and/or the material of at least one of said isolating layers is selected to be different from the material of at least one of the other isolating layers.

12. Use of cable according to any one of the preceding claims as an AC power cable.

A cable, a method of constructing a cable, and use of a cable

ABSTRACT

The invention relates to a cable and to a method of constructing a cable with at least one cable core having a number of conducting layers which are mutually separated by isolating layers, where said conducting layers include electrical conductors which are arranged helically with predetermined pitch angles. At least one of said isolating layers has a thickness different from the thickness of at least one of the other isolating layers, and/or at least one of said isolating layers includes material which is different from the material of at least one of the other isolating layers.

The invention further relates to the use of an AC cable according to the invention as a power cable.

Figure 2 should be published

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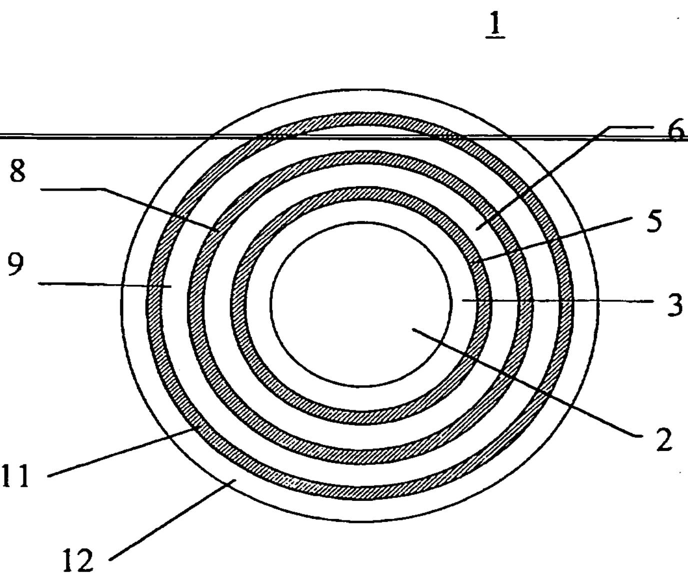

FIG. 1

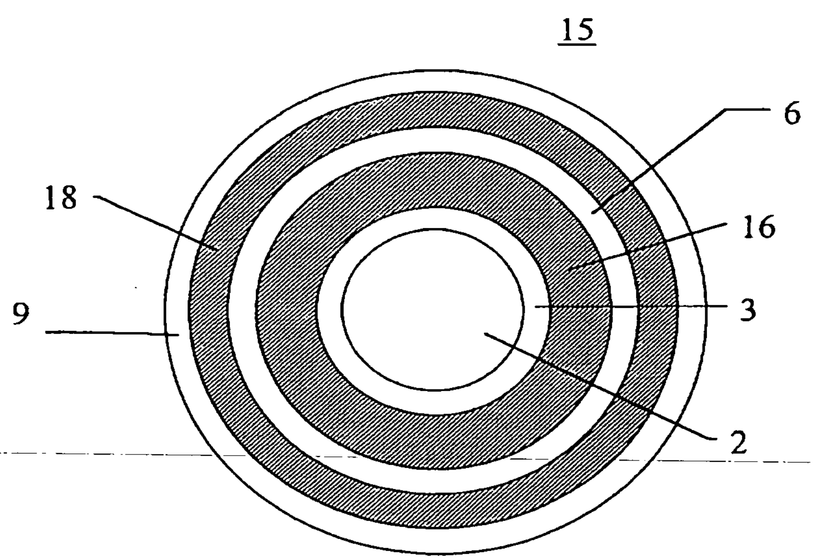

FIG. 2

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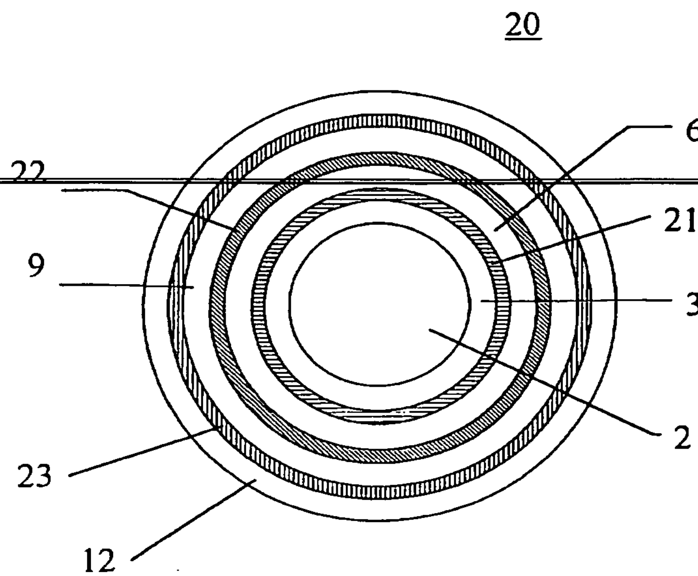

FIG. 3

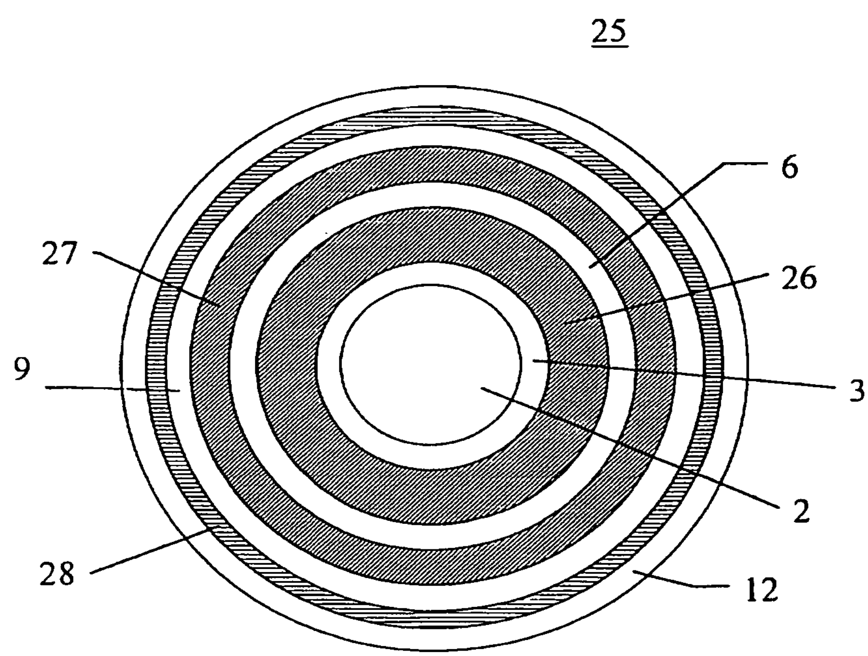

FIG. 4